Chapter 1 Introduction

1.1 Definition and classification

Kimberlites are relatively rare among terrestrial magmas, but their intimate relationships with diamonds make kimberlites important to the scientific and exploration communities. Significant international efforts over more than fifty years have been made to characterise the tectonic setting of kimberlites, their age, style of emplacement, composition and mineralogy. A specific theme of this research has been to investigate the origin of kimberlitic magmas and the P-T parameters and composition of the mantle source, including characterisation of melts and fluids involved in deep-seated mantle metasomatism.

Kimberlites have been found on all major continents (Fig. 1.1, Eckstrand et al., 1995; Pasteris, 1984). The most notable are found in South Africa, Tanzania, Angola, southwestern United States, Canada, Siberia and northern Western Australia. They occur in clusters or provinces that belong to thick Archaean and Palaeoproterozoic cratonic lithosphere, but can be also found within ancient basement fractures and other crustal lineaments. Kimberlites occur in intrusive bodies that were emplaced in a number of episodes throughout geological time. The oldest known kimberlite (~1600 Ma) is reported from the Kuruman province, South Africa (Shee et al., 1989); Precambrian kimberlites (~1000 Ma) are known in Africa, Brazil, Australia, India, Greenland and Siberia; Cambrian (~450 – 500 Ma) in China, Canada, South Africa and Siberia; Silurian – Devonian (370 – 410 Ma) in Siberia and United States; Permian (~200 Ma) in Botswana, Canada, Swaziland, Tanzania; Cretaceous (80 – 120 Ma) in Africa, Canada, India, Brazil, Siberia and United States; Eocene (~50 Ma) in Canada and Tanzania, and the youngest kimberlites are of Miocene age (~22 Ma) in northern Western Australia (Dawson, 1980; Dawson, 1989a; Pasteris, 1984).

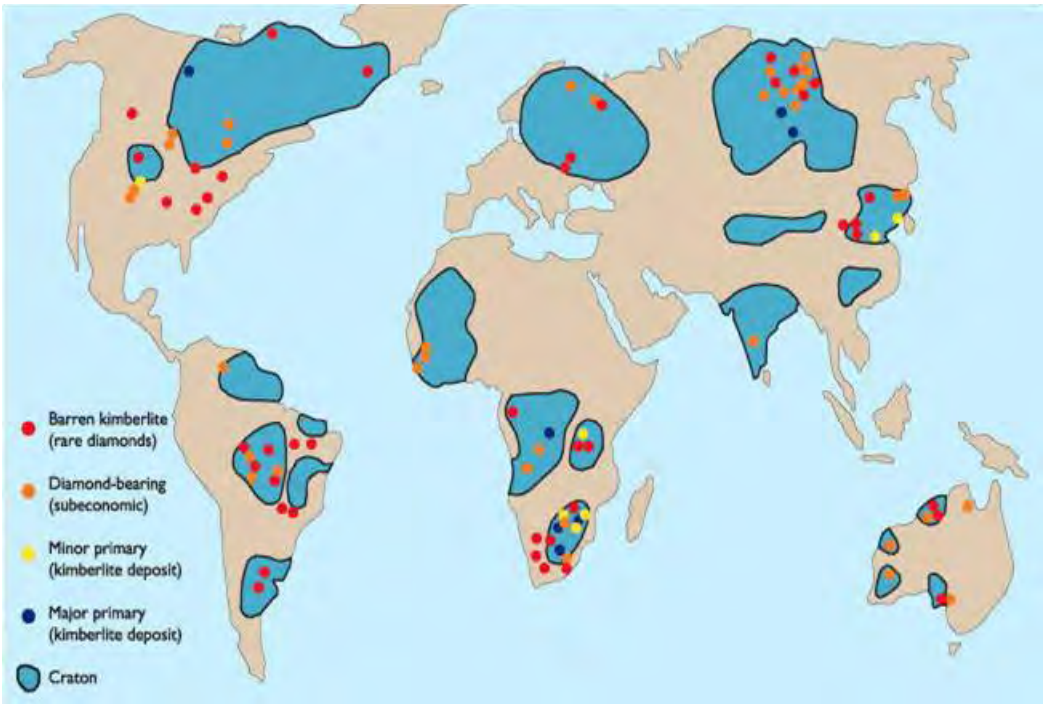

Figure. 1.1. Distribution of kimberlites worldwide (after Eckstrand *et al.*, 1995)

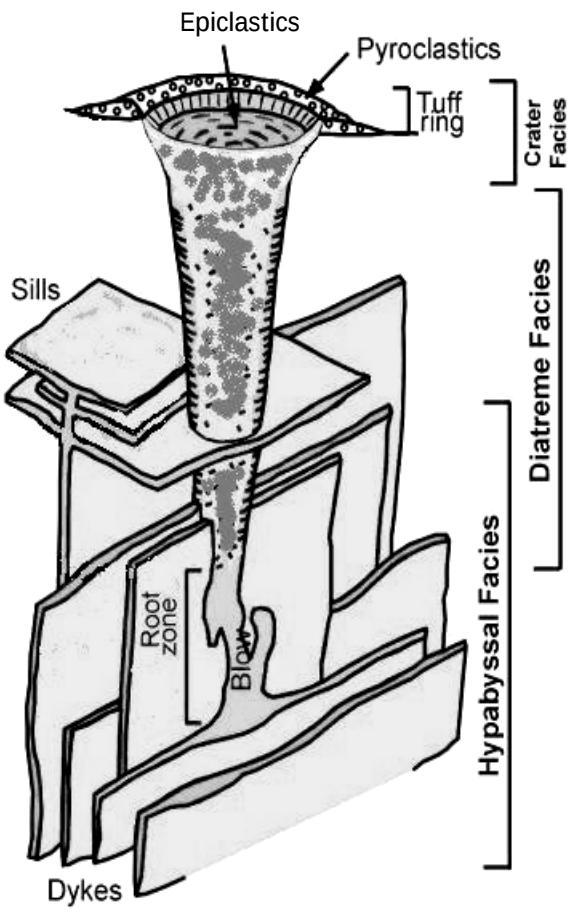

Figure. 1.2. Schematic cross section of kimberlite magmatic system (after Mitchell, 1986): Three textural groups: crater facies, diatreme facies and hypabyssal facies, which include diatreme root zone, dikes and sills.

The complexity of kimberlites (textural, mineralogical, petrographic and geochemical characteristics) has resulted in numerous definitions and classification models. The most accepted and well known definition was proposed and later modified by (Mitchell, 1979; Mitchell, 1986). This definition introduced the concept of a kimberlite clan and covers the whole spectrum of the kimberlitic rocks including kimberlite-hosted macrocryst/megacryst suites: "*Kimberlites are a clan of volatile-rich (dominantly carbon dioxide) potassic ultrabasic rocks. Commonly, they exhibit a distinctive inequigranular texture resulting from the presence of macrocrysts (and in some instances megacrysts) set in a fine grained matrix. The megacryst/macrocryst assemblage consists of rounded anhedral crystals of magnesian ilmenite, Cr-poor titanian pyrope, olivine, Cr-poor clinopyroxene, phlogopite, enstatite and Ti-poor chromite. Olivine is the dominant member of the macrocryst assemblage. The matrix minerals may include: second generation euhedral primary olivine and/or phlogopite, together with perovskite, spinel (titaniferous magnesian aluminous chromite, titanian chromite, members of the magnesian ulvospinel-ulvospinel-magnetite series), diopside (Al- and Ti- poor), monticellite, apatite, calcite, and primary late-stage serpentine (commonly Fe rich). Some kimberlites contain late-stage poikilitic eastonite phlogopites. Nickeliferous sulphides and rutile are common accessory minerals. The replacement of early-formed olivine, phlogopite, monticellite, and apatite by deuteric serpentine and calcite is common. Evolved members of the clan may be devoid of, or poor in, macrocrysts, and composed essentially of calcite, serpentine, and magnetite together with minor phlogopite, apatite and perovskite."*

Several classification models have been developed for kimberlites, with two models most commonly used:

The first model is based on textural-genetic variations among the kimberlitic rocks (Clement and Skinner, 1979). Most kimberlites occur in narrow pipe-like (diatremes) or dikes, and rarely in sills. Diatremes in cross section are vertical cone-shaped, relatively small (less than 1 km in diameter), widening upward bodies (Fig.1.2). Based on distinguishing textural features, three genetic facies of kimberlite rocks can be established: **crater**, **diatreme** and **hypabyssal**. Crater facies are represented by pyroclastic (formed as a result of eruptive forces) and epiclastic rocks (fluvial alteration of pyroclastic material) and are distinguished by sedimentary (layer) deposition.

Diatreme facies contain fragmented volcaniclastic kimberlitic material (pelletal lapilli, nucleated autoliths) with fine-grained diopside, serpentine and phlogopite matrix and various xenoliths. The absence of thermal, metasomatic/metamorphic effects and the lack of deformation and fractures associated with the intrusive body led to the assumption that this stage of emplacement occurs at relatively low temperatures. Hypabyssal facies represent root zones, dikes and sills. They are recognized by porphyritic texture and presence of abundant globular calcite-serpentine segregations and metamorphosed rock fragments. They are believed to crystallise from hot, volatile-rich kimberlite magmas.

The second classification model is based on recognition of wide variations in mineralogy, petrography and isotopic characteristics of kimberlites. This classification was originally proposed by Wagner (1914) and then re-enforced by Smith (1983). Two main compositional groups of kimberlites are recognized: Group-I or olivine rich (basaltic) kimberlites are characterised by prevailing olivine phenocrysts in groundmass and are distinctly enriched in CaO, H_2O and CO_2 and poorer in K_2O and SiO_2 in comparison to the other group. They are similar to a model Oceanic Island Basalt in terms of their Sr and Nd isotope ratios (i.e., $^{87}Sr/^{86}Sr$ = 0.703-0.705, $^{143}Nd/^{144}Nd$ = 0.51271-0.51277, and ε_{Nd} = -0.5 to +6). Group II or micaceous (phlogopite) kimberlites are richer in K_2O and isotopically similar to potassic volcanic rocks in continental settings (i.e, $^{87}Sr/^{86}Sr$ = 0.707-0.712, $^{143}Nd/^{144}Nd$ = 0.51208-0.51228, and ε_{Nd} = -7 to -12).

1.2 Mineralogy and chemistry of group-I kimberlite

Typical kimberlites are composed of xenocrysts and xenoliths of mantle and crustal origin set in a fine- to coarse-grained groundmass of serpentinized euhedral olivine, calcite, and minor silicate and oxide minerals (e.g., phlogopite, perovskite, Cr-spinel, magnetite) (Dawson, 1980; Mitchell, 1986; Mitchell, 1989; Pasteris, 1984). The typical groundmass component, comprising up to 50 vol% of the rock, is thought to represent crystallized kimberlite melt (Mitchell, 1986; Mitchell, 1989). But in almost all kimberlite occurrences groundmass is invariably altered by secondary processes.

Olivine is the most abundant silicate phase in kimberlites and usually present in two generations. First generation olivine is represented by fragmental or rounded macrocrysts and ranges in composition from Fo_{94} to Fo_{77}. Crystals are homogeneous, but narrow rims (< 200 μm) may be present. The rims are identical in compositions with the second generation, groundmass olivine. Groundmass olivine is represented by small (< 0.5 mm) euhedral to subhedral strongly zoned microphenocrysts that show a limited range of compositions from Fo_{87} to Fo_{93} (Mitchell, 1989). Olivine tends to be replaced or partially (veined and rimmed) by serpentine and carbonate. Thus in many kimberlitic rocks the dominant groundmass minerals are ***serpentine and carbonate***. Carbonate is commonly represented by calcite with accessory amount of dolomite and other carbonates.

Dawson (1980) and Mitchell (1986, 1989) summarized previous geochemical studies of the kimberlites and concluded that kimberlites are undersaturated ultrabasic rocks with low SiO_2 (25-35 wt%), Al_2O_3 (<5 wt %) and high MgO (15-43 wt%) and K_2O (up to 3 wt%) contents. The prevailing potassic nature of kimberlites is demonstrated by low Na_2O/K_2O (≤ 0.5) values. Trace element compositions of kimberlites are characteristically enriched in light rare earth elements (LREE) compared to other ultramafic rocks, but strongly depleted in heavy rare earth elements (HREE) (Dawson, 1980; le Roex et al., 2003; Mitchell, 1986; Pasteris, 1984; Wedepohl and Muramatsu, 1979).

1.3 Problems related to identification of the kimberlite melt

Kimberlite magmas, are believed to be derived from the Earth's mantle at >150 km (Dawson, 1980; Haggerty, 1999; Mitchell, 1989), deeper than any other known terrestrial magma type. Thus, kimberlites may offer the best available probe into origin and composition of mantle-derived melts and fluids and their behaviour en route to the surface. Many kimberlites are enriched in mantle-derived xenoliths that can provide information regarding subcratonic mantle and lithosphere, including characterization of melts and fluids involved in deep-seated mantle metasomatism. However, the composition of parental kimberlite melts and their primary volatile element abundances are still largely unknown. Research into identification of the kimberlite liquids has been hampered by several factors:

1. Most significant among these is the presence of variable amounts of mineral grains and mineral aggregates that are probably unrelated to the kimberlite crystallisation (xenocrysts and xenoliths), but are hard to separate from true phenocrysts and cognate inclusions, especially in altered rocks. This problem is reflected in the definition of the kimberlite rock as "*both a contaminated and altered sample of its parent melt*" (Pasteris, 1984).

2. Another problem relates to syn-emplacement and syn-crystallisation degassing of volatiles (CO_2 and H_2O), which is assumed to be significant in kimberlitic magmas (Clement et al., 1984; Mitchell, 1986; Skinner and Clement, 1979). The loss of magmatic volatiles complicates quantification of the parental melt composition if the latter is inferred from bulk rock analyses.

3. In most cases kimberlites are severely modified by syn- and post-magmatic changes that have altered the original alkali and volatile element abundances. Significant CO_2 and H_2O abundances are attributed respectively to carbonate minerals (calcite and dolomite) and serpentine (+ other H_2O-bearing magnesian silicates). It is still debatable whether all measured H_2O in kimberlites had a magmatic origin or was partly or completely introduced post-emplacement (Deines and Harris, 1995; Sheppard and Dawson, 1975).

In attempting to overcome these problems and characterise the composition of the kimberlite parental melt (including its volatile content),saveral approaches are used, e.g., studies of aphanitic kimberlites, experimental and theoretical modelling, and studies of diamond-hosted inclusions.

1.3.1 Studies of aphanitic kimberlites

Relatively rare, especially in hypabyssal facies, aphanitic kimberlites probably represent the best material to approximate the composition of primitive kimberlitic melt. (Price et al., 2000). Macrocrysts in these kimberlites are absent or present in small amount (<5 vol%). A number of recent publications have described several examples of aphanitic kimberlites from the DuToitspan kimberlite dyke, Bultfontein pipe, Wesselton Floors sill and Uintjiesberg kimberlite diatreme of South Africa, and from the Jericho, Leslie and Aaron, kimberlite pipes in the central Slave Province, Canada (Fedortchouk

and Canil, 2004; Harris et al., 2004; le Roex et al., 2003; Price et al., 2000). The primary kimberlite magma as inferred from these studies has a composition of 19-27 wt% SiO_2; 15-27 wt% MgO; 2.2 wt% Al_2O_3; 6.5-9.3 wt% FeO_t; 15-25 wt% CaO, 1-2 wt% K_2O, 12-19 wt% CO_2 and ~5 wt% H_2O with high Mg# (86-93 mol%) and high concentration of Ni (800–1400) and Cr (1300–2800). This composition is indicative of small degrees of partial melting (0.4-1.5 %) of carbonate-bearing garnet lherzolite at ~60 kbar (see below). In comparison to macrocrystal kimberlites, aphanitic kimberlites in general are more enriched in CaO and CO_2. The high CO_2 contents in these samples suggest lesser degrees of degassing during transport and emplacement of the kimberlite melt, and may provide a minimum estimate of CO_2 contents of kimberlite magmas.

1.3.2 Experimental studies

Numerous phase equilibria experiments on synthetic and natural kimberlitic and related melt compositions (e.g., nephelinite, melilitite, carbonatite, peridotite), always with addition of H_2O + CO_2, have been performed in order to better understand the genesis of kimberlite magmas (e.g., review of earlier works by Eggler, 1989; Wyllie, 1980; Wyllie, 1987; Wyllie, 1989). However, many important parameters of kimberlite generation, including pressure at the beginning of melting, concentrations of H_2O and CO_2 in primary magmas, and the composition of the source material, are still debatable.

Some experimental studies on phase relations in kimberlitic systems showed that liquids similar to the average kimberlite composition can be produced by partial melting of mantle peridotites at pressures >60 kbar (Eggler and Wendlandt, 1979; Girnis et al., 1995; Kesson et al., 1994; Ringwood et al., 1992). The presence of carbonate in the source material is probably not a necessary condition, because the high concentrations of CO_2 and other incompatible elements may be obtained by very low degree of melting of primitive or depleted mantle peridotites.

Other experiments demonstrated that the near-solidus melts of carbonated lherzolite are carbonatitic (Dalton and Presnall, 1998a; Dalton and Presnall, 1998b; Gudfinnsson and Presnall, 2003; Ryabchikov et al., 1993). They can grade into a spectrum of alkaline silicate melts (kimberlitic to nephelinitic) with increasing degree of melting (Gudfinnsson and Presnall, 2003; Hirose, 1997). This transition has been

studied at different pressures, and only at pressures greater than ~40 kbar with increasing degree of melting do the initial carbonatitic melts acquire a kimberlitic "flavour". In experiments with natural spinel lherzolite with added CO_2 the solidus melt is carbonatitic at 50 kbar and 1440^{o}C (Ryabchikov et al., 1993). With increasing temperature above the solidus, SiO_2 and MgO contents of the melt increase and CaO decreases (Ryabchikov et al., 1993), and melts become more kimberlitic (Dalton and Presnall, 1998a; Gudfinnsson and Presnall, 2003). The generation of kimberlites by very small degrees of melting is fully supported by geochemical evidence (Nelson et al., 1988). Crystallisation of kimberlite melts at high mantle pressure conditions is shown experimentally to exhaust the silicate components and generate carbonate-rich magmas (Girnis et al., 2005).

Experimental work has also suggested that kimberlite sources reside in metasomatised lithosphere "*only recently metasomatised, in the case of Group I kimberlites*" (Eggler, 1989), or in asthenosphere.

Another thrust of experimental studies has been directed towards evaluation of the P-T parameters, and effects of different volatiles and media composition on diamond nucleation and growth. Based on the results of these experiments, diamond formation is most likely in fluid-bearing alkaline-carbonate-rich silicate melts (e.g., Arima et al., 1993; Edgar and Charbonneau, 1993; Litvin and Spivak, 2003; Pal'yanov et al., 2002a; Pal'yanov et al., 1999; Pal'yanov et al., 2002b). High-K pyroxenes (1.2 wt.% K_2O) similar to those found as microinclusions in garnets in the diamondiferous rocks were crystallised from a K-poor silicate liquid coexisting with a potassium carbonate (or chloride) melt at P ~ 70 kbar and T > 1200^{o} C (Perchuk and Yapaskurt, 1998). Furthermore, the experiments with diamond growth in the potassium carbonate system (C–K_2CO_3–KCl) at 70-77 kbar and 1050–1420^{o}C showed a strong catalytic effect of Cl on diamond nucleation and growth (Tomlinson et al., 2004).

1.3.3 Inclusions in diamonds

The chemical stability of diamonds and their strength make them ideal time capsules for preserving mineral and fluid inclusions trapped during growth and

transport. These inclusions may contain crucial clues to the chemical and physical characteristics of the environment under which diamond is formed.

Mineral inclusions in diamonds are widespread, and they include silicate (garnet, olivine, clinopyroxene and orthopyroxene), oxides, sulphides and rare carbonate minerals, but other minerals are also present. Most mineral inclusions belong to peridotitic or eclogitic parageneses, providing valuable P-T parameters for their formation (900-1300^{o}C and 40-50 kbar). Some clinopyroxene inclusions in diamond are characterized by high potassium contents (up to 1.5 wt% of K_2O; Harlow and Veblen, 1991) and imply that diamonds containing such high potassium clinopyroxene may have grown in a highly K-enriched environment at very high pressure.

Over the last 10-15 years, developments in analytical techniques such as Fourier transform infrared (FTIR) spectroscopy, cathodoluminesence (CL), transmission electron microscopy, etc. have allowed studies of submicrometer fluid inclusions trapped in diamonds. Diamonds from Yakutian kimberlites have revealed large abundances of Cl, K, Ca, Ti, Rb, Sr, Nb and Ba in the central parts (nucleation seeds) of octahedral peridotitic diamonds (Bulanova et al., 1998). This implies that nucleation of diamonds occurred in a volatile-rich silicate melt highly enriched in LILE (K, Ba, Rb, Sr) and HFSE (Nb, Ti, Zr). Inclusions trapped in cuboid diamonds from the Udachnaya pipe show mineral assemblage (carbonates, olivine, apatite, graphite and silicate glasses) similar to some types of carbonatites with low water and silica contents (Zedgenizov et al., 2004). This evidence has been used to argue for the presence of a carbonatitic melt in the diamond growth environment. Reported uncommon $MgCO_3$ and $CaCO_3$ phases in association with typical clinopyroxene inclusions in diamond from Namibia (Leost et al., 2003) also point to a significant role for carbonate melt in diamond formation.

Another direction of diamond studies has been dedicated to inclusions in “coated” diamonds. Coated diamonds are composed of clear octahedral cores surrounded by fibrous overgrowths with abundant tiny volatile-rich inclusions (e.g., Guthrie et al., 1991; Navon et al., 1988; Schrauder and Navon, 1994). The compositions of these submicrometer inclusions form two compositional trends towards a carbonatitic fluid and towards a hydrosaline liquid (brine). The association of both fluids with the

silicate mineral inclusions, belonging either to the peridotitic or eclogitic paragenese is notable (Burgess et al., 2002; Izraeli et al., 1999; Izraeli et al., 2001; Izraeli et al., 2004; Johnson et al., 2000; Klein-BenDavid et al., 2004; Navon et al., 1988; Schrauder and Navon, 1994; Tomilenko et al., 1997; Turner et al., 1990). The carbonatitic fluid is rich in K_2O, Na_2O, CaO, FeO, MgO, and P_2O_5 and its composition was approximated as $K_{11}Na_{21}Ca_{11}Mg_{26}Fe_7Ba_2Si_{10}Al_3P_2C_{l5}$ (Klein-BenDavid et al., 2004). The brine composition is roughly $(K,Na)_8(Ca,Fe,Mg)_4SiO(CO_3)_4Cl_{10}(H_2O)_{28\text{-}44.}$ Izraeli et al. (2001) pointed out that the mineral phases detected in fluid-rich micro-inclusions in cloudy diamonds from Koffiefontein, are similar to those found as individual mineral inclusions in Koffiefontein and other diamonds.

What still remains to be understood is why the high alkali content shown by inclusions in diamonds is not reflected in the compositions of common kimberlites (e.g., Na_2O is invariably <0.3 wt%). The expected increase in the carbonate component as a result of olivine fractionation and/or silicate-carbonate melt immiscibility (Clarke and Mitchell, 1975; Clement, 1975; Kjarsgaard and Hamilton, 1988; Mitchell, 1975) is also not reflected in the high concentrations of alkali elements (Na and K) in kimberlite rocks. Moreover, low abundances of these elements relative to elements of similar incompatibility are not easily reconciled with the expected geochemical characteristics of low-degree mantle melts, even if residual phlogopite is present in the source peridotite (le Roex et al., 2003).

The typically low alkali contents of kimberlites parallels observations from magmatic carbonatites, another rock type genetically related to low-degree mantle melts (including kimberlites). Alteration of the carbonate fraction towards essentially alkali-free calcitic compositions has been advocated since the discovery of modern alkali natrocarbonatite lavas from Oldoinyo Lengai volcano and their altered counterparts (Clarke and Roberts, 1986; Dawson, 1962; Dawson, 1989b; Dawson et al., 1987; Deans and Roberts, 1984; Gittins and McKie, 1980; Hay, 1983). Rapid degradation of alkali carbonates and dissolution of alkali chlorides in crustal environments may be responsible for depriving kimberlites (carbonatites) of their original sodium and potassium. But how do we learn about magmatic alkali abundances in kimberlites without having an “Oldoinyo Lengai” example among kimberlites?

Another important issue, still unsolved, centres on information about volatile components (water, carbon dioxide, chlorine) in mantle-derived kimberlite melts and fluids. Although these volatiles were originally delivered from the mantle, only CO_2 and H_2O have so far been considered important in kimberlite genesis and mantle processes, such as mantle metasomatism (e.g., transfer of elements, melt-peridotite reactions, and formation of chemical heterogeneities). By contrast, high abundances of chlorine recorded in brine inclusions in diamonds are not evident in any kimberlite samples and there is a very little knowledge about storage and transport of Cl in the mantle, its influence on partial melting, and its association with other volatiles in deep processes.

1.4 Aims of this study

A search through numerous descriptions of altered kimberlites and so-called "fresh" kimberlites (but still with serpentine and low Na_2O abundances) revealed a report on rocks collected from a borehole (> 350 m) in the Udachnaya-East pipe in the Daldyn-Alakit region of Siberia (Marshintsev et al., 1976). These rocks were described as "unaltered" because neither primary nor secondary serpentine was present in the groundmass or after olivine. The Udachnaya-East pipe became very popular among mantle and diamonds researchers of the abundant and unaltered mantle xenoliths, ranging from diamondiferous eclogite and garnet peridotite to spinel peridotite and pyroxenite (e.g., Boyd et al., 1997; Griffin et al., 1996; Jacob et al., 1994; Jerde et al., 1993; Shimizu et al., 1997; Sobolev, 1977; Sobolev et al., 1999; Wirth and Matsyuk, 2005). Unaltered groundmass olivine attracted casual attention from workers studying melt and fluid inclusions (Popivnyak and Laz'ko, 1979; Sobolev et al., 1989). However, surprisingly little is known about basic petrographic, mineralogical and geochemical characteristics of these exceptionally fresh kimberlite rocks.

The aim of my study is to close the gap in our knowledge about these kimberlites by analysing major, volatile and trace elements, radiogenic and stable isotopes, and doing comprehensive analysis of olivine and olivine-hosted crystal, melt and fluid inclusions. By studing these unaltered kimberlites, I aim to recognise compositions and records of magmatic processes that are either no longer preserved or obscured in common kimberlites. From the very beginning of this work, I became aware of significant scientific potential of my kimberlite samples to characterise the deepest

mantle-derived melts, their volatile abundances, temperature, crystallisation history, and magmatic immiscibility. In the course of this study, the original goal of detailing basic petrological and geochemical characteristics was generating additional targets. Although many of them have been under scrutiny of leading research laboratories for years, my study can provide principally new insights into their resolution. However, realistically they are beyond the scope of a PhD project.

Chapter 2 Kimberlite from the Udachnaya pipe: regional and local geology.

2.1 Regional geology

The Siberian diamondiferous kimberlite province is located within the central, eastern and southern parts of the Siberian Platform (Fig III. 1), one of the major Precambrian crustal units in Eurasia covering an area of 4,500.000 km^2 (Nalivkin, 1973). Provinces and terranes within the Platform have been mapped on the basis of known crustal shear zones, boreholes to basement, crustal xenolith suites in kimberlites, and by regional-scale geophysical data. The Platform is surrounded by major Phanerozoic suture zones formed during the assembly of the Pangean supercontinent. The boundaries of the Siberian Platform are defined by the North-Siberian or Khatangian Depression in the north, Aldan-Vitim Massif and Baikal-Patom folded area in the south, Verkhoyansk foldbelt in the east and the Sayano-Taymyr fault zone, separating the Siberian Platform from the "young" West Siberian plate, on the west.

Although the tectonic history of the Siberian Platform is very complicated, two major structural levels can be defined: Archaean - Early Proterozoic and Late Proterozoic - Phanerozoic. The Archaean and Early Proterozoic structures make up the crystalline basement of the Siberian Platform, and they can be recognised in four major massifs – the Aldan and Anabar shields, and Eastern Sayan and Yenisei uplifts. Archaean rocks comprise granite-gneisses, amphibolites and carbonates. According to geophysical data and studies of xenoliths in kimberlites, the rocks beneath the Archaean basement are very heterogeneous in composition and are represented mainly by garnet-bearing ultramafic (pyrope-peridotite and pyroxenites) and basic (eclogites and grospydites) rocks (Sobolev, 1977). Highly-aluminous mineral assemblages (garnet-sillimanite-K-spar-quartz-biotite or garnet-hypersthene-sillimanite-quartz-K-spar) are also found among basement rocks as xenoliths in kimberlites (1995). All other parts of the Siberian platform are covered by a thick (2.5 km in average) sequence of the Neo Proterozoic and Phanerozoic sedimentary and volcanic rocks divided into four major structural horizons: Riphean-Vendian, Early Palaeozoic, Middle- Late Palaeozoic and Mesozoic.

The Riphean-Vendian deposits do not outcrop at present-day surface. Deep drilling reveals their presence at the margins of the Siberian Platform in the form of a 2-2.5 km thick sequence of the terrigenous and carbonate sediments. The Early Palaeozoic deposits are widespread and cover most of the Siberian Platform. The Cambrian horizons (1.5-2.5 km thick) are distributed throughout the Platform, except the most elevated parts and consist of marine clay-carbonate deposits in the east and north-west, and of evaporites, shallow-water and lagoon deposits in the south-west. The Ordovician rocks (0.4 – 2 km thick) conformably overlie the Cambrian sequences and comprise dolomites, limestones, sandstones and marls. The Middle- Late Palaeozoic deposits are present in the central part of the Platform, mainly as clay-carbonate strata deposited in a shallow-water environment. Terrigenous carbonates, evaporites and salt-bearing sediments with sills and dykes of alkaline basalts of the same age are also present. The Mesozoic terrigenous coal-bearing deposits include the Late Carboniferous - Early Triassic Siberian Traps (flood basalts and basaltic sills and dykes).

Kimberlite magmatism of the Siberian (Yakutian) province is believed to relate to deep-seated fractures along a major hinge zone between the Anabar Shield (between the Yenisei and Lena Rivers) and the relatively downwarped area during the crust movements associated with the folding of the Verkhoyansk belt (Leontiev and Kadensky, 1957). It has been suggested that these fractures are arranged in geometric patterns, and that differential movements on different segments of the block faulted basement are probably connected with deep tectonics in the upper mantle (see reviews in (Davidson, 1967a; Dawson, 1967). Reactivation at different times along the deep-seated faults resulted in the formation of several kimberlite fields and clusters (e.g., Malo-Botuobinck, Daldyn-Alakit, Olenek, Anabar, Muna, Pri-Lena, etc) varying in age from the Ordovician (450 Ma) to Late Cretaceous (100-85 Ma).

2.1.1 Short history of kimberlite discovery in the Siberian Platform

In the 1930's, Profs V.S. Sobolev and V.S. Trofimov noted the similarity between the ancient basement rocks of Siberia and South Africa, and indicated a possibility of major diamond deposits in the Siberian Platform. Active prospecting followed the as a result of a specific government decision in 1938; however, it was unclear where and how to look for diamonds. Field-based research was carried out in the Urals, Kola Peninsula, East Sayany, and the Enisei taiga. The recognition by the Soviet geologists of pyrope and ilmenite as useful indicator minerals led to discovery of the first Siberian diamond on August 7, 1949 in the Vilyuy River sediments (Tungus Expedition party, chief geologist Grigory Fainshtein).

The discovery of the first Siberian kimberlite pipe reflects the research efforts of two Soviet geologists, Natalia Sarsadskikh and Larissa Popugayeva. From 1950, Natalia Sarsadskikh headed the research unit developing a "schlich" (alluvial heavy mineral concentrate) map of the Siberian platform, which would help to find diamond indicator minerals. Their field work in the basin of the Markha River was focused on the search for pyrope and picroilmenite, the most common indicators of kimberlites and diamonds. They advocated exploration in this area because it had previously been described as a zone of tectonic rifting, where the emplacement of kimberltic magma into the upper crust was most possible. Both indicator minerals and a tiny diamond were eventually found. On 21 August, 1954 on the left bank of the Dyakha river (headwaters of the Markha river), Larissa Popugayeva and field assistant Feodor Belikov discovered the Zarnitsa kimberlite pipe, then the first in the USSR and outside South Africa. The kimberlite proved to be diamond-bearing. This was the beginning of the diamond mining industry in Yakutia. A year later, in 1955 the two most productive pipes - Mir and Udachnaya (15 km west of Zarnitsa) were discovered within 10 days of each other. At the end of the 1956 field season, 20 pipes had been found.

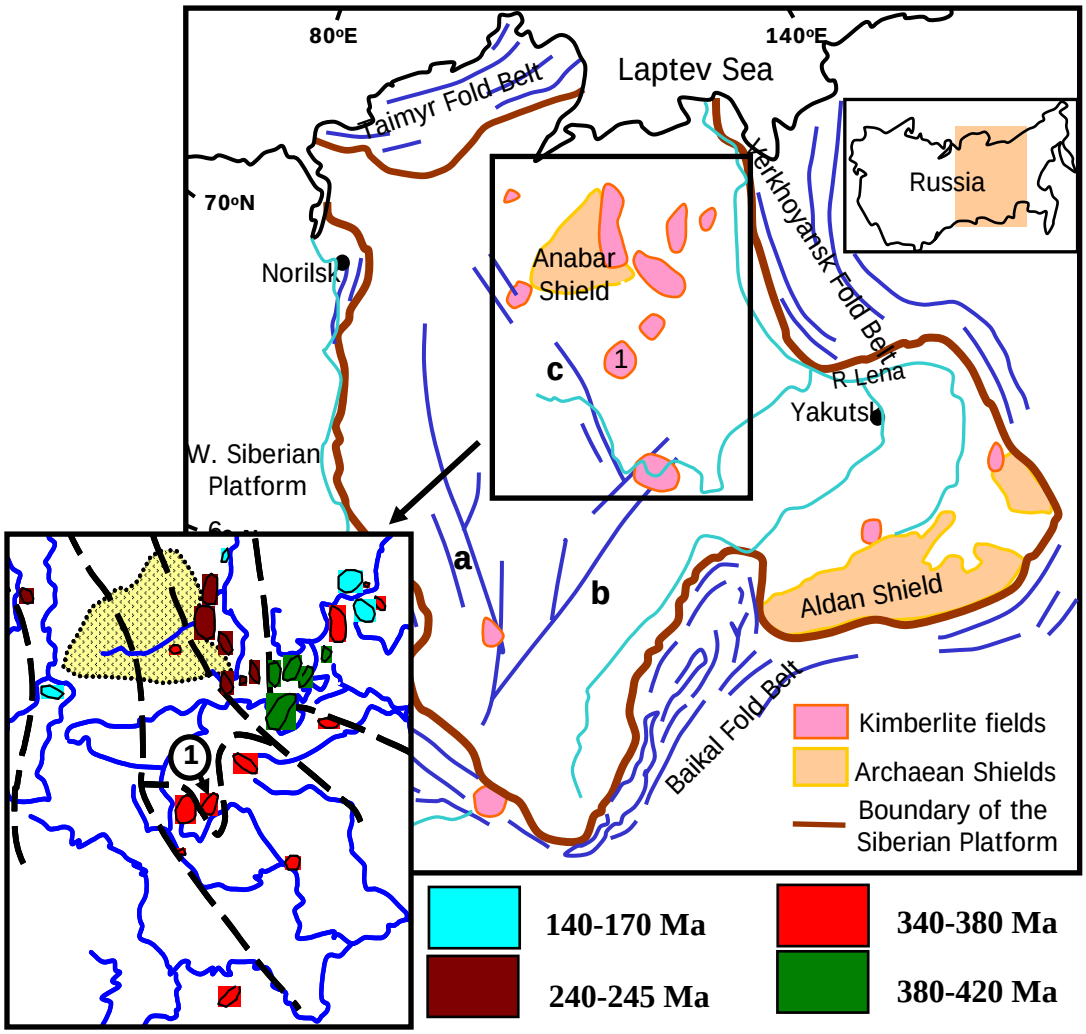

Figure 2.1. Map of Siberian Platform with major kimberlitic groups after Pearson *et al.*, 1995: orange shaded regions are exposed Archaean cratons, blue lines – major fold zones; a – Angara-Yenisei zone, b – Angara-Vilyui zone, c – Vilyui-Kotui zone: 1 – Daldyn-Alakit kimberlite group. Insert: Detailed map of the central and eastern part of the Siberian platform (after Griffin, *et al.*, 1999), showing local high level fracture zones, kimberlite fields location and their age; 1 - Daldyn field, containing Udachnaya pipe at the north-west border.

By 1964 some hundreds of kimberlite pipes and dykes were discovered throughout the Siberian Platform, scattered in small groups over an area of 1,500.000 km^2. To date more then 500 pipes have been found in the Siberia Platform, located mainly in the central areas of the Archaean-Proterozoic basement. There are now several major diamondiferous areas in Siberia (Fig.2.1): 1. Vilyui, including the Malo-Batuoba and Daldyn-Alakit regions; 2. Olenek (Lower and Middle Olenek); 3. Muna; 4. The Aldan region (Upper Aldan and Ingily); and 5. East Sayan province. Almost all of the kimberlite-bearing basement areas belong to the Sakha Republic (formely Yakutia). More than 40% of this territory is beyond the polar circle, and almost all territory of the republic lies in the zone of permafrost. The deepest level of permafrost (1500 m) was found in the upper Markha River, the site of the Zarnitsa and Udachnaya pipes.

2.2 Local geology of the Udachnaya kimberlite pipe

Information about the geological environment, and structure, size and composition of the former Soviet Union kimberlite pipes is extremely scarce in the published literature. As the confidential reports were not available to me, the descriptions below are very sketchy, and are mainly based on a few publications (Davidson, 1967a; Field-guide, 1995; Frantsesson, 1970; Marshintsev et al., 1976; Sobolev, 1977; Sobolev, 1989; Zinchuk et al., 1993)

The Daldyn-Alakit kimberlite region, the best studied part of the Siberian diamondiferous province, comprises > 50 pipes, ranging from 400-700 m in diameter. This kimberlite region includes two kimberlite fields – Daldyn and Alakit. Most pipes are tuff-breccias essentially devoid of unaltered olivine, but some contain many blocks of massive fresh kimberlite. A remarkable characteristic of this region is that it contains more pipes with fresh, unaltered olivine than any other kimberlite region within the Siberian diamondiferous province. About 10% of the intrusions exhibit either two adjacent channelways or repeated intrusion of magma through the same chimney. The Udachnaya pipe, the best known example of these twin diatremes, is located in the north-west part of the Daldyn field on the left bank of Pyropovy Creek. It consists of two adjacent bodies (East and West) with an uneven figure of 8-like outline in plan. At a depth of 250-270 m the two bodies become separated (Fig. 2.2). Country rocks are

represented by the Early Ordovician massive dolomites, limestones, argillites and sandstones and the Late to Middle Cambrian dolomites, marls, argillites and limestones. The contact between country rocks and the kimberlite body is subvertical and well defined structurally. Both kimberlite and country rocks show significant alteration, and mechanical destruction and brecciation is common near contacts. Both pipes are enriched in peridotitic nodules.

It is worthy of note that on the Siberian Platform and at the site of the Udachnaya pipe, the ground-waters are highly concentrated brines (>300 g/l), containing Cl, K, Na and Ca and high abundances of Sr (up to 5 g/kg) and Ba (up to 1440mg/l) (1995). More detailed chemical characteristics of the mine pit brines, derived in this study, will be given in Chapter 5.

Another interesting fact is reported by (Davidson, 1967a) – diamond drilling at the Udachnaya pipe was interrupted by outbursts of flammable gas from a depth of 360 m, of composition (in wt%) 50.9 H_2, 30.4 CH_4, 12.8 N_2, 3.7 C_2H_6, 1.9 O_2, 0.032 He, 0.016 Ar, and 0.3 wt% of undetermined hydrocarbons.

Based on stratigraphic relationships, both intrusions are Devonian (~350 Ma), and most investigators believed that the Western pipe was formed earlier. A range of ages from 389 to 335 Ma have been suggested for the Udachnaya pipes. They are based on dating phlogopite (Sarsadskikh et al., 1966), Rb-Sr data for carbonates and phlogopites (Maslovskaja et al., 1983), U-Pb zircon ages for nearby diamondiferous kimberlites (Sobolev, 1984), on stratigraphic relationships (Pearson et al., 1995a), on Sm-Nd mineral ages for eclogitic xenoliths (Snyder et al., 1993), and on K-Ar data for clinopyroxene inclusions in Udachnaya diamonds (Burgess et al., 1992). Perovskite in the Udachnaya kimberlite has been dated at 353-367 Ma by SHRIMP U-Pb analysis (Kinny et al., 1997). Zircon ages obtained for two other pipes in Daldyn-Alakit kimberlite field are 350 Ma (Davis, 1978). Based on Rb-Sr and U-Pb data obtained in this study, the age lies between 342 and 351 Ma (averaging at 347 Ma) (Chapter 5 and (Maas et al., 2005).

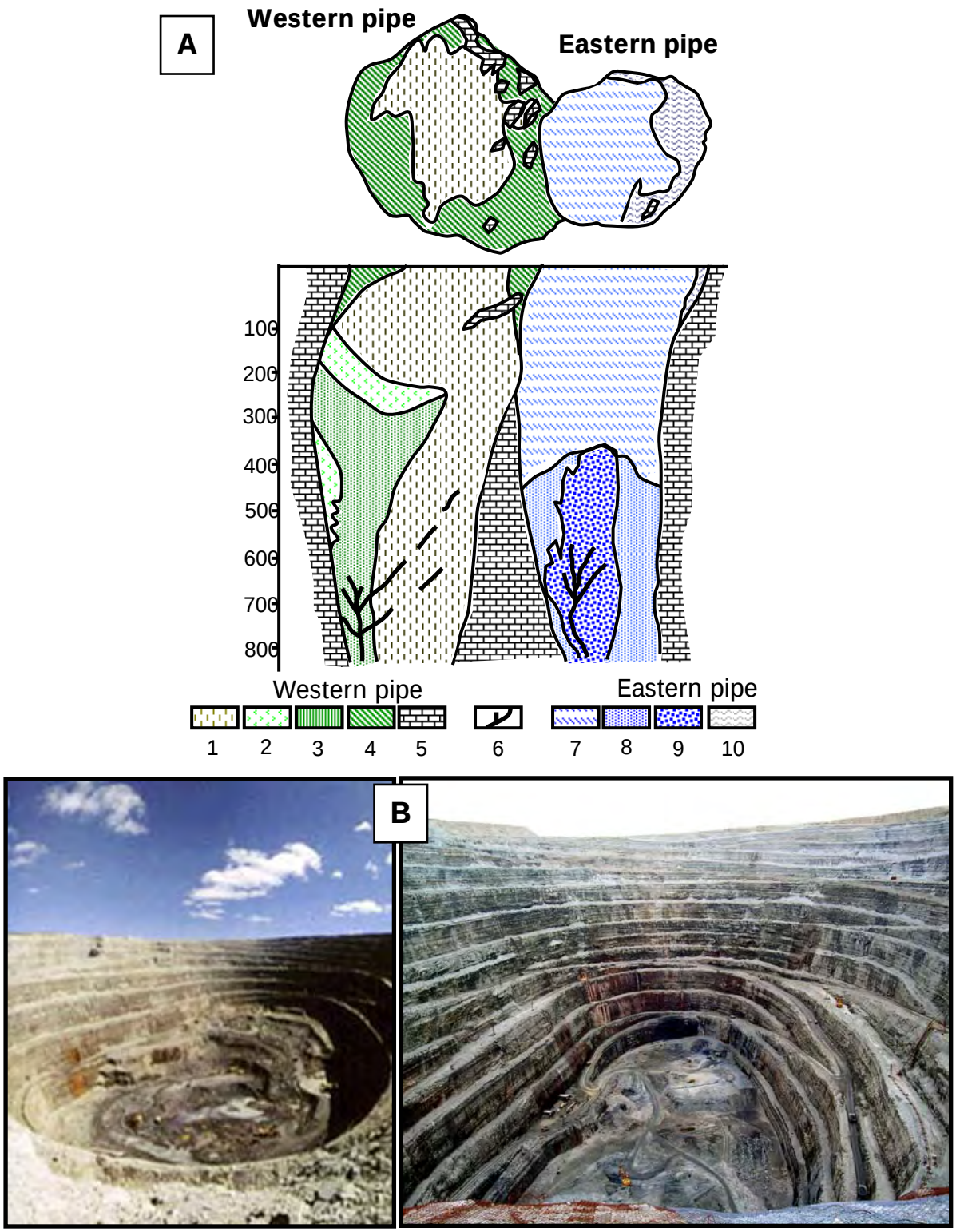

Figure 2.2. Arial (B, Photo courtesy of Dr. V Sharygin), plan and cross section (A) views of Udachnaya kimberlite pipes after Zinchuk *et al*., 1993: Western pipe: 1-kimberlite breccia, 2-kimberlite with fluidal texture, 3-kimberlite with porhpyritic texture, 4-contact intensively altered kimberlite, 5-country rocks and large xenolith of the country rocks, 6-vein kimberlite; Eastern pipe: 7-porphyry kimberlite, 8-kimberlite breccia, 9-porphyry kimberlite with fresh unaltered olivine, 10-kimberlite autobreccia.

The kimberlite rocks near the contact between the two bodies of the Udachnaya pipe progressively change from kimberlite breccias with massive texture and abundant fresh olivine phenocrysts of the Eastern body, through intensely altered (serpentinised) and crushed rocks, to the altered kimberlite breccias of the Western body. Groundmass textures, mineralogy and chemistry of the kimberlite rocks comprising both bodies of the Udachnaya pipe suggest that, two intruding phases can be recognized. Most workers agree that the porphyritic kimberlite relates to the early stage of intrusion, whereas the kimberlite breccias manifest the final stages of the pipe emplacement.

The Eastern and Western bodies of the Udachnaya kimberlite pipe are different from each other in terms of mineralogy, petrography, composition, and degree of alteration. As the alteration of the Western pipe can be considered as typical of this rock type, the rocks of the Eastern body are unique in having lesser alteration, and in parts they are completely fresh. As my study was focussed on the unaltered rocks, a more detailed description of the Eastern pipe is given below.

2.2.1 Characteristics of the Udachnaya-East pipe

The multiple intrusive events accompanying kimberlite magma emplacement are reflected in the complex structure of the Udachnaya-East pipe. At least five kimberlite varieties are recognized - dark porphyritic kimberlite with mostly serpentinised olivine grains, kimberlite breccias, kimberlite autobreccias, porphyritic kimberlite with fresh olivine and veined kimberlite. The pipe is characterized by a large amount (0.3-0.6 vol%, in some parts up to 5 vol%) and different types of mantle xenoliths. The distribution of xenoliths in the pipe body is irregular, most being concentrated in the central part of the body. Their size varies from small (a few mm) particles to huge (up to several m) blocks. There are three main groups of mantle xenoliths: 1. Lherzolites are the most abundant (63 %) type with large variations in composition; 2. Eclogites and pyroxenites (6 %); and 3. Complex xenoliths (41%) represented by altered lherzolites with veins of ilmenite-rich pyroxenites or xenoliths with large variations of garnet composition in a single sample.

2.2.1.1 Petrographic characteristics

Two distinct types of rocks have been described as forming the Udachnaya-East pipe – massive porphyritic kimberlites with a large proportion of fresh olivine, and kimberlite breccias.

Porphyritic kimberlites comprise a significant part of the Udachnaya-East body and are represented by dark, massive rocks with serpentinized olivine in a fine-grained matrix of phlogopite- serpentine- carbonate. Carbonate occurs as microcrysts of calcite 0.02-0.1 mm in size. At ~350 m depth and deeper a particularly fresh variety of porphyritic kimberlite has been found. These rocks were described as dark-grey massive kimberlite, characterized by unaltered euhedral-subhedral olivine phenocrysts set in a dominantly carbonate matrix (Marshintsev et al., 1976). A considerably lower amount of xenolithic material than in the kimberlites from the upper part of pipe was also noted (Marshintsev et al., 1976). At deeper levels of the kimberlite body the amount of serpentine in the groundmass gradually decreases, possibly because of reduction in the convective inflow of alteration fluids. At the same time the amount of carbonates in the groundmass increases, but the origin of carbonates (i.e., primary vs secondary) is still a matter of considerable debate in the Russian literature (Golovin et al., 2003; Mal'kov and Bobolovich, 1977; Marshintsev et al., 1976; Ukhanov et al., 1988; Zinchuk et al., 1993)

Kimberlite breccias are subordinate compared to porphyritic kimberlites, and characterised by a large amount of sedimentary, metamorphic and ultramafic xenoliths (5-20 vol%) and autoliths. Olivine porphyroclasts and microcrysts (5-30 vol%) are the main constituents of the kimberlitic breccia. Groundmass consists of serpentinized olivine, rare microcrysts of phlogopite, and carbonate cemented by serpentine-carbonate mixture.

Intensive mining of the Udachnaya pipe revealed widespread chlorides (mostly halite, NaCl) as dispersed masses in groundmass and massive multi-mineral segregations of halite, serpentine, anhydrite, carbonates and hydrous iron oxides (Pavlov and Ilupin, 1973). The amount of chlorides in the groundmass increases with depth, and recently a large number of salt-carbonate nodules were recovered from the

600-800 m level of the mine. (V. Sharygin, pers. comm.). These nodules vary in size from relatively small (5-10 cm) to large blocks (Fig. 2.3). Dr V. Sharygin divided salt-carbonate nodules into three mineralogical groups: halite-sylvite, halite-sylvite-shortite and halite-sylvite-shortite –northypite, and has provided me with a few small samples of salt-carbonate nodules for the study. Results are given in Chapters 3, 5 and 6. In the Russian literature, the origin of chlorides in the Udachnaya-East pipe is usually linked to concentrated chloride groundwaters (brines), circulating in the crust around the pipe (Pavlov and Ilupin, 1973; Golovin et al., 2003).

2.2.1.2 Diamonds in the Udachnaya pipe kimberlite

The Udachnaya pipe is one of the most diamond-productive mines in the word and the most productive in the Siberian kimberlite province (Table 2.1). According to an article in the Russian daily newspaper "PRAVDA" (8 July 2003) - "In 2003, several unique diamonds were found in the Udachnaya Pipe - a big black industrial diamond of 700 carats, several gem diamonds of 80 carats each and rare gem crystals. The latter include a diamond of a tobacco color of 232.7 carats, found in February, and a tender lemon diamond of an ideal form of 66 carats without natural distortions found in March". Distribution of diamonds within the body of the Udachnaya pipe remains regular or changes very little with depth. Most diamonds have octahedral or rhombododecahedral habits (Fig. 2.3). A large amount of diamond fragments is also present, usually with traces of corrosion on broken surfaces.

Table 2.1 Current Annual Production at World's Major Mines, 2001, source: Mining Journal, London, August 23, 2002

Country	**Carats**	**Tonnes**	**US$/carat**	**Value**
	('000)	**('000)**		**($ m)**
South Africa				
Venetia	4,977	4,602	85	423
Namaqualand	808	6,083	180	145
Finsch	2,465	4,768	70	173
Premier	1,637	3,102	75	123
Kimberley	550	3,766	110	61
Baken	65	5,835	400	26
Koffiefontein	145	2,299	225	33
Russia				
Udachnaya	11,500	9,000	85	978
Australia				
Argyle	26,000	15,100	11	286
Merlin	70	270	110	8

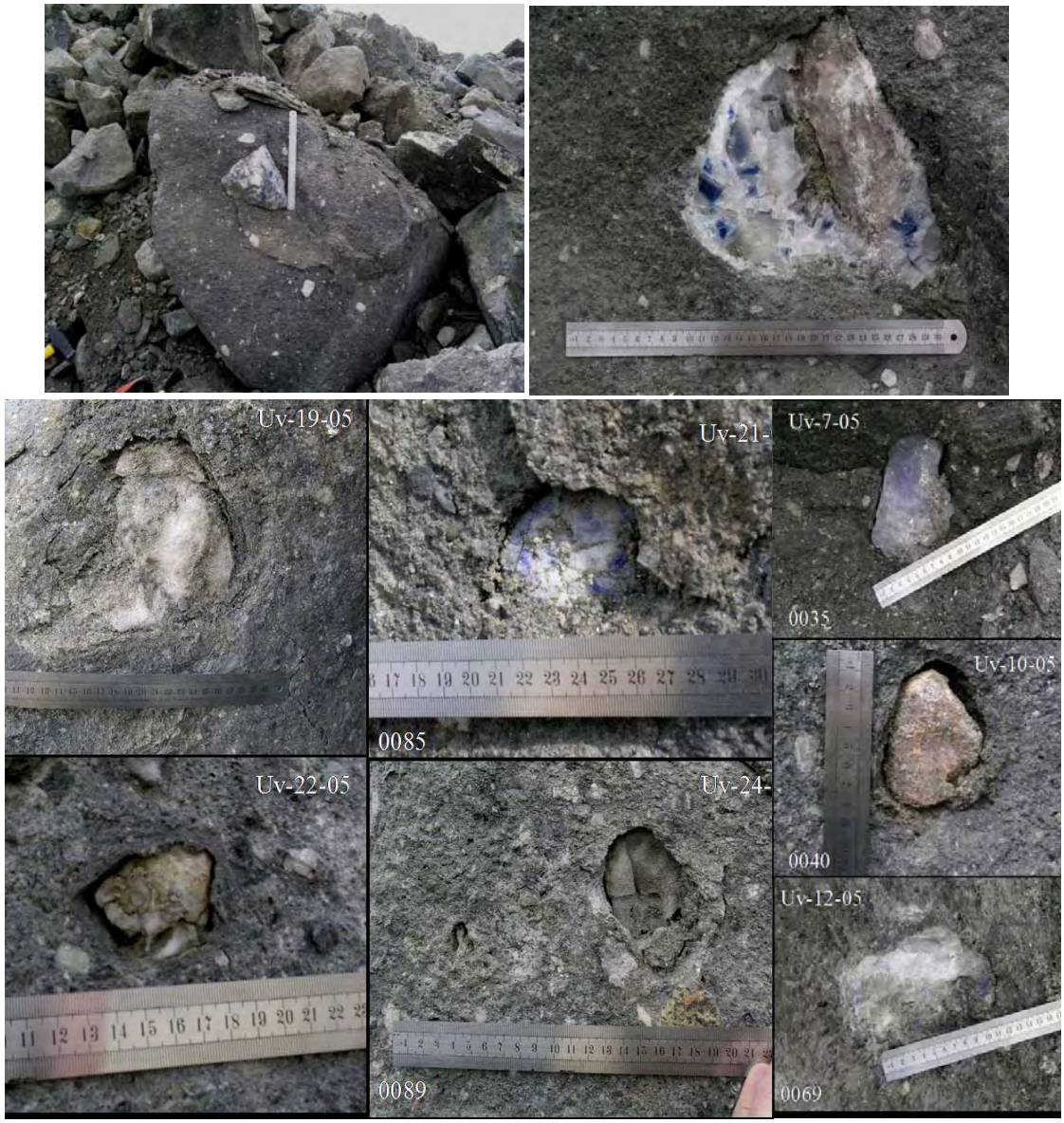

Figure 2.3. Salt-carbonate nodules from the Udachnaya-East kimberlite pipe. Photo courtesy of Dr. V. Sharygin

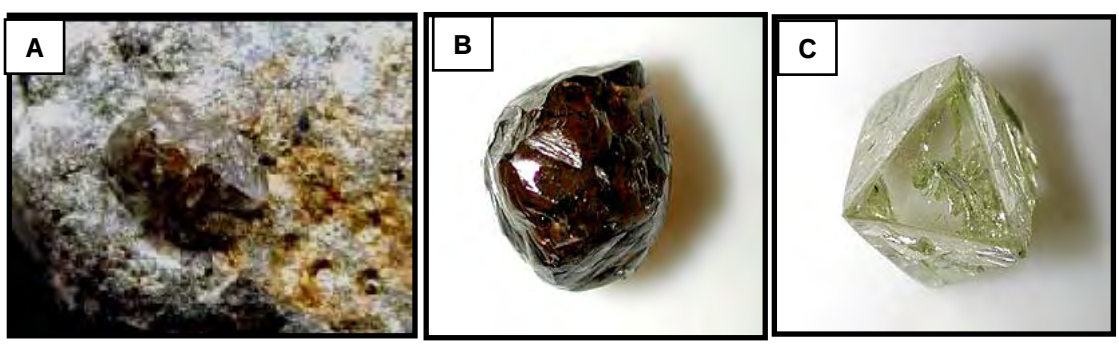

Figure 2.4. Diamonds found in the Udachnaya kimberlite pipe A - large smoky colored diamond (0.7x0.35cm) in kimberlite; B – dodecahedron diamond 8x8x7 mm in size; C – octahedron diamond 8x8 mm in size